The Higgs, Flavor and Large A_t in Extended GMSB

Jared A. Evans

jaredaevans@gmail.com

Department of Physics

University of Illinois, Urbana-Champaign

arxiv:1303.0228 – JAE, D. Shih
arxiv:1501.XXXX – JAE, D. Shih, A. Thalapillil
More In Progress – JAE, D. Shih, A. Thalapillil

A Higgs at $\sim$ 125 GeV is a *big* problem for the MSSM

Higgs at 125 GeV

A problem for the MSSM

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To accommodate, we need either: (Draper, Meade, Reece, Shih 2011)

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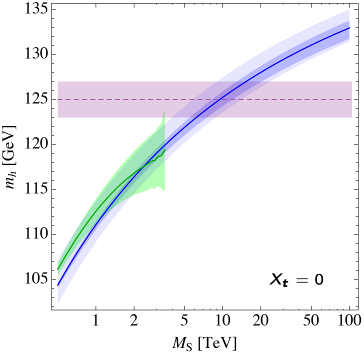
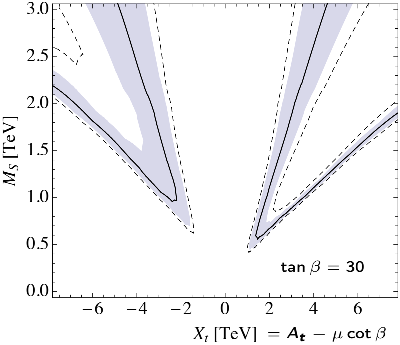


Large A-terms $\sim \sqrt{6} M_S$



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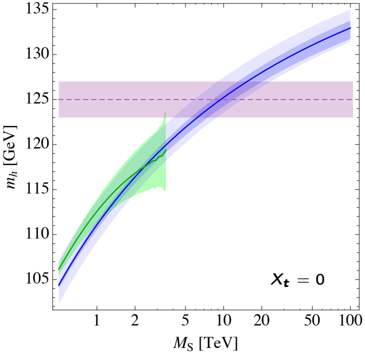

Large tuning: $\Delta \sim 5000$

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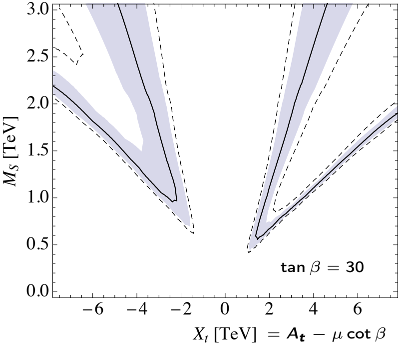

Smaller tuning: $\Delta \sim 500$

Higgs at 125 GeV

A *HUGE* problem for GMSB

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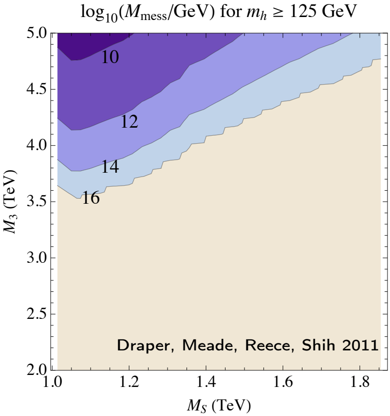

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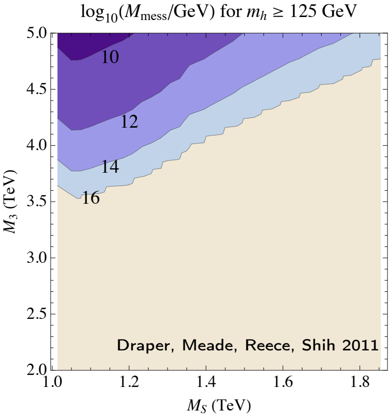

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$\Rightarrow$ huge tuning $\Delta \sim 5000$

Extended GMSB has MSSM-messenger terms in the superpotential

$$W \supset \lambda H_u \Phi \Psi + y_t H_u Q_3 U_3 + X(\Phi\bar{\Phi} + \Psi\bar{\Psi}) + \text{h.c.}$$

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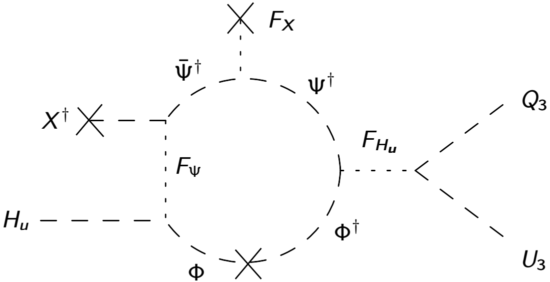

A-terms are *bilinear* terms: $A_t = y_t\left(A^{H_u} F^\dagger_{H_u} H_u + A^Q F^\dagger_{Q_3} Q_3 + A^U F^\dagger_{U_3} U_3\right)$

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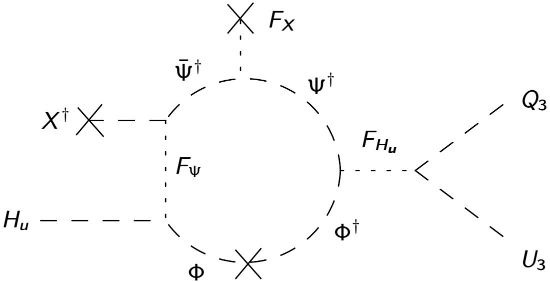

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With a low messenger scale and large A-terms, can we reduce tuning?

Target: $\Delta \sim 500$, i.e., the best the MSSM can get!

Outline

$$A_t = y_t \left(A^{H_u} F^\dagger_{H_u} H_u + A^Q F^\dagger_{Q_3} Q_3 + A^U F^\dagger_{U_3} U_3 \right)$$

Survey Tuning in EGMSB Models with a 125 GeV Higgs

Survey Flavor in EGMSB Models with Lower Tuning

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Survey Tuning in EGMSB Models with a 125 GeV Higgs

- Need EGMSB couplings that contain H_u, Q_3 or U_3 ($Q \equiv Q_3$)
- Write all couplings compatible with $SU(5)$ unification ($N_{eff} \leq 6$)
- Define each model by ONE EGMSB coupling (31 models total)
- Scan each model to determine smallest tuning possible
- Examine LHC phenomenology in models with lower tuning

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Survey Flavor in EGMSB Models with Lower Tuning

- Relax flavor alignment, i.e., $\kappa_3 Q_3 \Phi\tilde{\Phi} \to \kappa_i Q_i \Phi\tilde{\Phi}$
- How much misalignment permitted before flavor constraints?
- What does the future hold?

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Not true in models with MSSM-Messenger mixing!

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Derived a new technique to treat these couplings
(Details too technical for this talk)

Types of models

Two types of models

Type I			Type II	
MSSM-Messenger-Messenger			MSSM-MSSM-Messenger	
Higgs	Q-class	U-class	w/ mixing	w/o mixing
$\lambda H_u \Phi \tilde{\Phi}$	$\lambda Q \Phi \tilde{\Phi}$	$\lambda U \Phi \tilde{\Phi}$	$\lambda H_u Q \Phi_U$	$\lambda U E \Phi_{\bar{D}}$

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Tuning:	???	???	???	???	???
Flavor:	???	???	???	???	???

We will assess the tuning and flavor in these models!

Lightning GMSB Review

$$W \sim X\Phi\tilde{\Phi} + \{\text{MSSM yukawas}\}$$

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$$M_r \sim N_{eff}\, g_r^2 \tilde{\Lambda} \qquad m^2_{soft} \sim 2N_{eff}\, C_r g_r^4 \tilde{\Lambda}^2 \qquad (C_r \text{ quadratic Casimirs})$$

$$A\text{-terms} = 0$$

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$$W \sim \kappa H_u \sum^{N_m} \Phi_i \tilde{\Phi}_i$$

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$$\delta m_{H_u}^2 = d_H \kappa^2 \left((d_H + d_\phi)\,\kappa^2 - 2C_r g_r^2 - \frac{16\pi^2}{3} h\left(\frac{\Lambda}{M}\right) \frac{\Lambda^2}{M^2} \right) \tilde{\Lambda}^2$$
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Type I Higgs

EGMSB Soft Formulas

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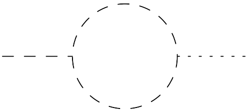

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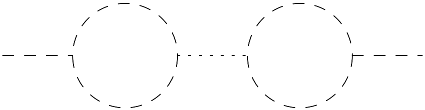

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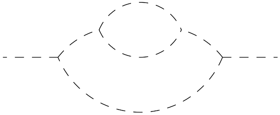

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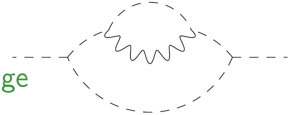

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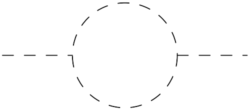

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one-loop term

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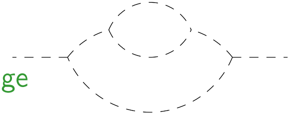

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through yukawa

one-loop term

Solving for $m_h = 125$ GeV

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Moreover, given $\left(\kappa, \frac{\Lambda}{M}\right)$, increasing M increases m_h monotonically

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Given an EGMSB model, κ, F, and M: spectra completely determined

Moreover, given $\left(\kappa, \frac{\Lambda}{M}\right)$, increasing M increases m_h monotonically

PLAN:

1. **Scan over $\left(\kappa, \frac{\Lambda}{M}\right)$**
2. **Dial M to solve for $m_h = 125$**
3. **Quantify how finely-tuned that point is**

A tuning measure for GMSB

Tuning is ambiguous – quantifying an intrinsically qualitative measure

e.g., vary with respect to F? $\sqrt{F}$? F^2? $F^{\frac{3}{2}}$? F^{18}? $\frac{F}{M}$? $\frac{F}{M^2}$? $\frac{F^2}{M^3}$? etc.

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Our fine-tuning measure, Δ_{FT}, should

1. provide an accurate comparison between GMSB scenarios
2. never overlook contributions which cancel in a uncorrelated way
3. never introduce contributions which cancel in a correlated way
4. assign comparable sensitivity to uncorrelated terms which cancel

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where $\Delta_i \equiv \frac{d \log m_z^2}{d \log \Lambda_i^2}$ with $\Lambda_i \in \{g_3^2\Lambda,\ y_t^2\Lambda,\ \kappa^2\Lambda,\ \mu,\ \Lambda_{1-loop}\}$

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Varying Λ_{1-loop}^2 is varying $\frac{F^4}{M^6} h\left(\frac{F}{M^2}\right)$

Type I Higgs models have a "little $A - m_H$ problem" (Craig, Knapen, Shih, Zhao 2012)

$$A_{H_u} = -d_H \kappa^2 \tilde{\Lambda} \qquad \text{Note: } A_t = y_t \left(A_{H_u} + A_{Q_3} + A_{U_3}\right)$$

$$\delta m_{H_u}^2 = A_{H_u}^2 + d_H \kappa^2 \left(d_\phi \kappa^2 - 2 C_r g_r^2 - \frac{16\pi^2}{3} h\left(\frac{\Lambda}{M}\right) \frac{\Lambda^2}{M^2} \right) \tilde{\Lambda}^2$$

Increasing $A_t \Rightarrow$ increasing $m_{H_u}^2$

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$$m_Z^2 \sim -2\left(\mu^2 + m_{H_u}^2\right)$$

$$\Rightarrow \Delta \sim \frac{d \log m_z^2}{d \log A_t^2} = 2\frac{A_t^2}{m_z^2} \sim 12 \frac{M_S^2}{m_z^2} \sim 3000$$

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We expect tuning to be bad in these models!

Type I Higgs
Tuning

Little $A - m_H$ problem tells us tuning should not approach $\Delta \sim 500$

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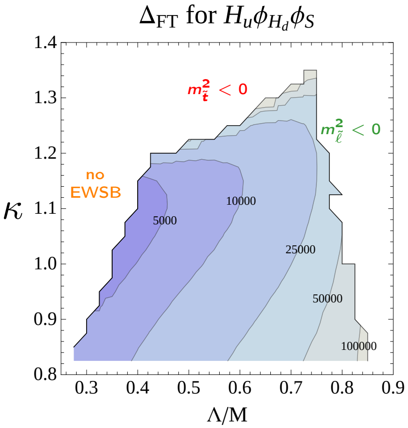

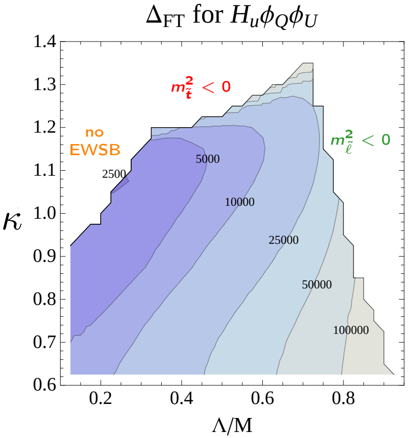

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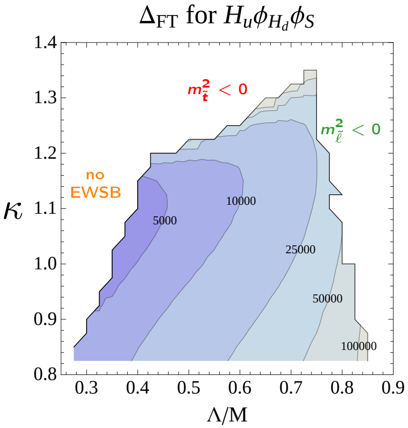

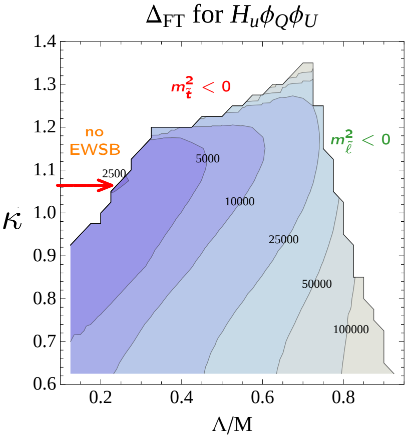

At best, Type I Higgs has $\Delta \sim 2500$ ($5\times$ worse than best case MSSM)

(Much worse than this in models not shown!)

	Type I			Type II	
	Higgs	Q-class	U-class	w/ mixing	w/o mixing
	$\lambda H_u \Phi \tilde{\Phi}$	$\lambda Q \Phi \tilde{\Phi}$	$\lambda U \Phi \tilde{\Phi}$	$\lambda H_u Q \Phi_U$	$\lambda U E \Phi_{\bar{D}}$
Tuning:	BAD	???	???	???	???
Flavor:	MFV	???	???	???	???

#	Model	d_Q	d_ϕ	C_r
I.8	$Q\phi_{\overline{10},\bar{Q}}\phi_{1,S}$	N_m	7	$\left(\frac{1}{30},\frac{3}{2},\frac{8}{3}\right)$
I.9	$Q\phi_{\bar{5},D}\phi_{\bar{5},L}$	N_m	5	$\left(\frac{7}{30},\frac{3}{2},\frac{8}{3}\right)$
I.10	$Q\phi_{10,U}\phi_{5,H_u}$	1	5	$\left(\frac{13}{30},\frac{3}{2},\frac{8}{3}\right)$
I.11	$Q\phi_{10,Q}\phi_{5,\bar{D}}$	2	6	$\left(\frac{1}{10},\frac{3}{2},4\right)$

#	Model	d_U	d_ϕ	C_r
I.12	$U\phi_{\overline{10},\bar{U}}\phi_{1,S}$	N_m	4	$\left(\frac{8}{15},0,\frac{8}{3}\right)$
I.13	$U\phi_{\bar{5},D}\phi_{\bar{5},D}$	$2N_m$	4	$\left(\frac{2}{5},0,4\right)$
I.14	$U\phi_{10,Q}\phi_{5,H_u}$	2	4	$\left(\frac{13}{30},\frac{3}{2},\frac{8}{3}\right)$
I.15	$U\phi_{10,E}\phi_{5,\bar{D}}$	1	4	$\left(\frac{14}{15},0,\frac{8}{3}\right)$

$$W \sim \kappa Q \sum^{N_m} \Phi_i \tilde{\Phi}_i \qquad A_Q = -d_Q \kappa^2 \tilde{\Lambda}$$

$$\delta m_Q^2 = d_Q \kappa^2 \left((d_Q + d_\phi)\kappa^2 - 2C_r g_r^2 - \frac{16\pi^2}{3} h\left(\frac{\Lambda}{M}\right)\frac{\Lambda^2}{M^2} \right)\tilde{\Lambda}^2$$

$$\delta m_{H_u}^2 = -3 d_Q y_t^2 \kappa^2 \tilde{\Lambda}^2 \qquad \delta m_{H_d}^2 = -3 d_Q y_b^2 \kappa^2 \tilde{\Lambda}^2$$

$$\delta m_U^2 = -2 d_Q y_t^2 \kappa^2 \tilde{\Lambda}^2 \qquad \delta m_D^2 = -2 d_Q y_b^2 \kappa^2 \tilde{\Lambda}^2$$

$$W \sim \kappa U \sum^{N_m} \Phi_i \tilde{\Phi}_i \qquad A_U = -d_U \kappa^2 \tilde{\Lambda}$$

$$\delta m_U^2 = d_U \kappa^2 \left((d_U + d_\phi)\kappa^2 - 2C_r g_r^2 - \frac{16\pi^2}{3} h\left(\frac{\Lambda}{M}\right)\frac{\Lambda^2}{M^2} \right)\tilde{\Lambda}^2$$

$$\delta m_Q^2 = -d_U y_t^2 \kappa^2 \tilde{\Lambda}^2 \qquad \delta m_{H_u}^2 = -3 d_U y_t^2 \kappa^2 \tilde{\Lambda}^2$$

#	Model	d_Q	d_ϕ	C_r
I.8	$Q\phi_{\bar{10},\bar{Q}}\phi_{1,S}$	N_m	7	$\left(\frac{1}{30}, \frac{3}{2}, \frac{8}{3}\right)$
I.9	$Q\phi_{\bar{5},D}\phi_{\bar{5},L}$	N_m	5	$\left(\frac{7}{30}, \frac{3}{2}, \frac{8}{3}\right)$
I.10	$Q\phi_{10,U}\phi_{5,H_u}$	1	5	$\left(\frac{13}{30}, \frac{3}{2}, \frac{8}{3}\right)$
I.11	$Q\phi_{10,Q}\phi_{5,\bar{D}}$	2	6	$\left(\frac{1}{10}, \frac{3}{2}, 4\right)$

#	Model	d_U	d_ϕ	C_r
I.12	$U\phi_{\bar{10},\bar{U}}\phi_{1,S}$	N_m	4	$\left(\frac{8}{15}, 0, \frac{8}{3}\right)$
I.13	$U\phi_{\bar{5},D}\phi_{\bar{5},D}$	$2N_m$	4	$\left(\frac{2}{5}, 0, 4\right)$
I.14	$U\phi_{10,Q}\phi_{5,H_u}$	2	4	$\left(\frac{13}{30}, \frac{3}{2}, \frac{8}{3}\right)$
I.15	$U\phi_{10,E}\phi_{5,\bar{D}}$	1	4	$\left(\frac{14}{15}, 0, \frac{8}{3}\right)$

$$W \sim \kappa Q \sum^{N_m} \Phi_i \tilde{\Phi}_i \qquad A_Q = -d_Q \kappa^2 \tilde{\Lambda}$$

$$\delta m_Q^2 = d_Q \kappa^2 \left((d_Q + d_\phi)\kappa^2 - 2C_r g_r^2 - \frac{16\pi^2}{3} h\left(\frac{\Lambda}{M}\right)\frac{\Lambda^2}{M^2} \right)\tilde{\Lambda}^2$$

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$$\delta m_U^2 = -2 d_Q y_t^2 \kappa^2 \tilde{\Lambda}^2 \qquad \delta m_D^2 = -2 d_Q y_b^2 \kappa^2 \tilde{\Lambda}^2$$

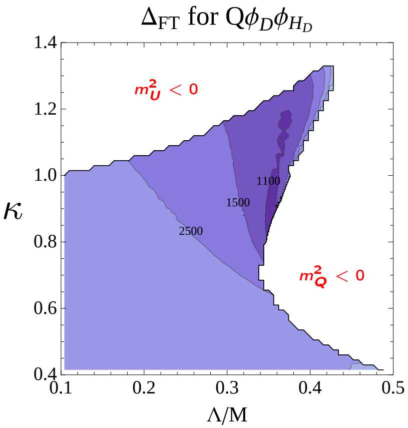
$$W \sim \kappa U \sum^{N_m} \Phi_i \tilde{\Phi}_i \qquad A_U = -d_U \kappa^2 \tilde{\Lambda}$$

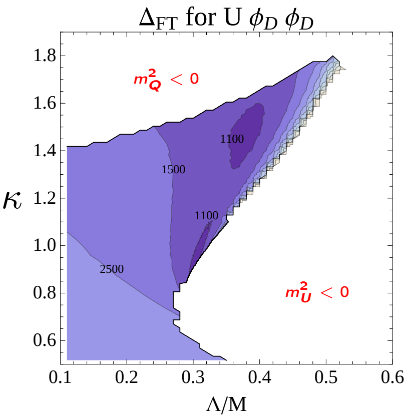
$$\delta m_U^2 = d_U \kappa^2 \left((d_U + d_\phi)\kappa^2 - 2C_r g_r^2 - \frac{16\pi^2}{3} h\left(\frac{\Lambda}{M}\right)\frac{\Lambda^2}{M^2} \right)\tilde{\Lambda}^2$$

$$\delta m_Q^2 = -d_U y_t^2 \kappa^2 \tilde{\Lambda}^2 \qquad \delta m_{H_u}^2 = -3 d_U y_t^2 \kappa^2 \tilde{\Lambda}^2$$

Little $A - m_{\tilde{t}}$? Not a problem!

Type I Squark Models
Tuning





Type I Squark Models

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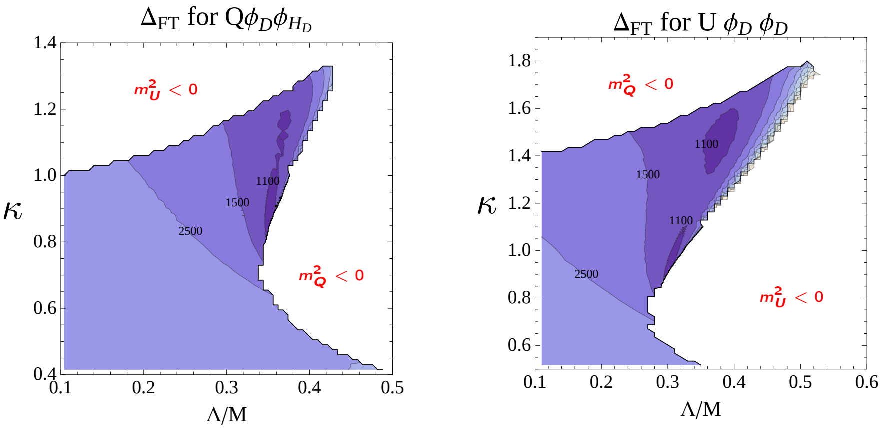
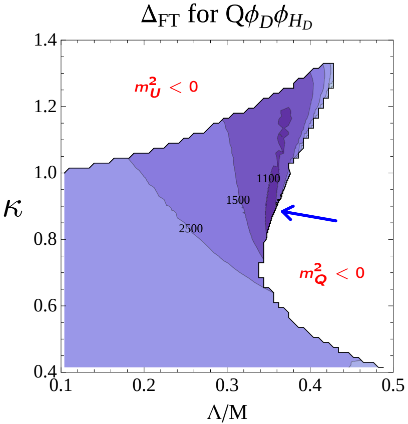
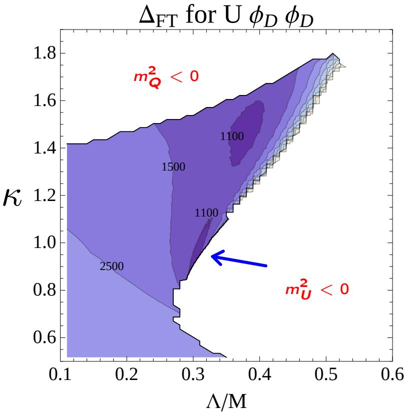


All Type I squark models similar, near $\Delta_{FT} \sim 1000$ ($2\times$ the best MSSM)

Type I Squark Models

Tuning





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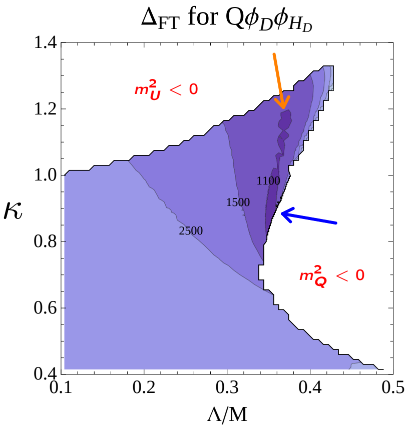
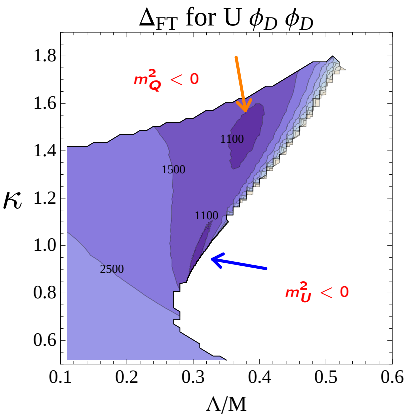
Best region right before 1-loop term drives m_Q^2 tachyonic

Type I Squark Models
Tuning





All Type I squark models similar, near $\Delta_{FT} \sim 1000$ ($2\times$ the best MSSM)

Best region right before 1-loop term drives m_Q^2 tachyonic

Good region before rising κ drives m_U^2 tachyonic

Type I Models

Tuning

#	Coupling	$\lvert\Delta b\rvert$	Best Point $\{\frac{\Lambda}{M}, \lambda\}$	$\lvert A_t\rvert / M_S$	$M_{\tilde{g}}$	M_S	$\lvert\mu\rvert$	Tuning
I.1	$H_u \phi_{\bar{5},L} \phi_{1,S}$	N_m	$\{0.375, 1.075\}$	1.98	3222	1842	777	3400
I.2	$H_u \phi_{10,Q} \phi_{10,U}$	$3N_m$	$\{0.25, 1.075\}$	1.99	3178	1828	789	2450
I.3	$H_u \phi_{5,\bar{D}} \phi_{\bar{10},\bar{Q}}$	4	$\{0.25, 1.3\}$	2.05	2899	1709	668	3200
I.4	$H_u \phi_{5,\bar{L}} \phi_{\bar{10},\bar{E}}$	4	$\{0.125, 0.95\}$	0.58	11134	8993	2264	4050
I.5	$H_u \phi_{\bar{5},L} \phi_{24,S}$	6	$\{0.225, 1.000\}$	0.54	13290	9785	3408	3850
I.6	$H_u \phi_{\bar{5},L} \phi_{24,W}$	6	$\{0.15, 1.025\}$	0.67	11835	8637	3259	3410
I.7	$H_u \phi_{\bar{5},D} \phi_{24,X}$	6	$\{0.3, 1.425\}$	2.04	3020	1743	576	3500
I.8	$Q \phi_{\bar{10},\bar{Q}} \phi_{1,S}$	$3N_m$	$\{0.534, 1.5\}$	2.82	4336	1274	2056	1015
I.9	$Q \phi_{\bar{5},D} \phi_{\bar{5},L}$	N_m	$\{0.353, 0.858\}$	2.67	4247	1342	2058	1015
I.10	$Q \phi_{10,U} \phi_{5,H_u}$	4	$\{0.51, 1.788\}$	2.65	4040	1318	2301	1275
I.11	$Q \phi_{10,Q} \phi_{5,\bar{D}}$	4	$\{0.378, 1.245\}$	2.76	4020	1257	2292	1260
I.12	$U \phi_{\bar{10},\bar{U}} \phi_{1,S}$	$3N_m$	$\{0.476, 1.622\}$	2.62	3815	1347	2070	1030
I.13	$U \phi_{\bar{5},D} \phi_{\bar{5},D}$	$2N_m$	$\{0.301, 0.908\}$	2.91	3829	1199	2061	1020
I.14	$U \phi_{10,Q} \phi_{5,H_u}$	4	$\{0.37, 1.352\}$	2.81	3575	1220	2312	1285
I.15	$U \phi_{10,E} \phi_{5,\bar{D}}$	4	$\{0.51, 1.972\}$	2.63	3526	1312	2310	1280

	Type I			Type II	
	Higgs	Q-class	U-class	w/ mixing	w/o mixing
	$\lambda H_u \Phi \tilde{\Phi}$	$\lambda Q \Phi \tilde{\Phi}$	$\lambda U \Phi \tilde{\Phi}$	$\lambda H_u Q \Phi_U$	$\lambda U E \Phi_{\bar{D}}$
Tuning:	BAD	GOOD	GOOD	???	???
Flavor:	MFV	???	???	???	???

Type II Models

EGMSB Formulas

#	Model	d_1	d_2	d_3	C_r
II.1	$QU\phi_{5,H_u}$	1	2	3	$\left(\frac{13}{30},\frac{3}{2},\frac{8}{3}\right)$
II.2	$UH_u\phi_{10,Q}$	2	3	1	$\left(\frac{13}{30},\frac{3}{2},\frac{8}{3}\right)$
II.3	$QH_u\phi_{10,U}$	1	3	2	$\left(\frac{13}{30},\frac{3}{2},\frac{8}{3}\right)$
II.4	$QD\phi_{\bar{5},H_d}$	1	2	3	$\left(\frac{7}{30},\frac{3}{2},\frac{8}{3}\right)$
II.5	$QH_d\phi_{\bar{5},D}$	1	3	2	$\left(\frac{7}{30},\frac{3}{2},\frac{8}{3}\right)$
II.6	$QQ\phi_{5,\bar{D}}$	2	2	4	$\left(\frac{1}{10},\frac{3}{2},4\right)$
II.7	$UD\phi_{\bar{5},D}$	2	2	2	$\left(\frac{2}{5},0,4\right)$
II.8	$QL\phi_{\bar{5},D}$	1	3	2	$\left(\frac{7}{30},\frac{3}{2},\frac{8}{3}\right)$

#	Model	d_1	d_2	d_3	C_r
II.9	$UE\phi_{5,\bar{D}}$	1	3	1	$\left(\frac{14}{15},0,\frac{8}{3}\right)$
II.10	$H_uD\phi_{24,X}$	3	2	1	$\left(\frac{19}{30},\frac{3}{2},\frac{8}{3}\right)$
II.11	$H_uL\phi_{1,S}$	1	1	2	$\left(\frac{3}{10},\frac{3}{2},0\right)$
II.12	$H_uL\phi_{24,S}$	1	1	2	$\left(\frac{3}{10},\frac{3}{2},0\right)$
II.13	$H_uL\phi_{24,W}$	$\frac{3}{2}$	$\frac{3}{2}$	1	$\left(\frac{3}{10},\frac{7}{2},0\right)$
II.14	$H_uH_d\phi_{1,S}$	1	1	2	$\left(\frac{3}{10},\frac{3}{2},0\right)$
II.15	$H_uH_d\phi_{24,S}$	1	1	2	$\left(\frac{3}{10},\frac{3}{2},0\right)$
II.16	$H_uH_d\phi_{24,W}$	$\frac{3}{2}$	$\frac{3}{2}$	1	$\left(\frac{3}{10},\frac{7}{2},0\right)$

$$W \sim \kappa X_1 X_2 \phi_{X_3}$$

$$\delta m^2_{X_1} = \left(d_1\left(\sum_i d_i\kappa^2 - 2C_r g_r^2 - \frac{8\pi^2}{3}h\left(\frac{\Lambda}{M}\right)\frac{\Lambda^2}{M^2}\right) + 2d_1d_3y^2_{123} - d_1^{2p}d_2y^2_{12p} + \frac{1}{2}d_1d_2^{pq}y^2_{2pq}\right)\kappa^2\tilde{\Lambda}^2$$

$$\delta m^2_{X_2} = \delta m^2_{X_1}\{1\leftrightarrow 2\}$$

$$\delta m^2_{X_a} = -\left(d_a^{1p}d_1y^2_{1ap} + d_a^{2p}d_2y^2_{2ap}\right)\kappa^2\tilde{\Lambda}^2$$

$$A_{X_{1,2}} = -d_{1,2}\kappa^2\tilde{\Lambda} \qquad A_t = y_t\left(A_{H_u} + A_{Q_3} + A_{U_3}\right)$$

Type II Models

EGMSB Formulas

#	Model	d_1	d_2	d_3	C_r
II.1	$QU\phi_{\mathbf{5},H_u}$	1	2	3	$\left(\frac{13}{30},\frac{3}{2},\frac{8}{3}\right)$
II.2	$UH_u\phi_{\mathbf{10},Q}$	2	3	1	$\left(\frac{13}{30},\frac{3}{2},\frac{8}{3}\right)$
II.3	$QH_u\phi_{\mathbf{10},U}$	1	3	2	$\left(\frac{13}{30},\frac{3}{2},\frac{8}{3}\right)$
II.4	$QD\phi_{\bar{\mathbf{5}},H_d}$	1	2	3	$\left(\frac{7}{30},\frac{3}{2},\frac{8}{3}\right)$
II.5	$QH_d\phi_{\bar{\mathbf{5}},D}$	1	3	2	$\left(\frac{7}{30},\frac{3}{2},\frac{8}{3}\right)$
II.6	$QQ\phi_{\mathbf{5},\bar{D}}$	2	2	4	$\left(\frac{1}{10},\frac{3}{2},4\right)$
II.7	$UD\phi_{\bar{\mathbf{5}},D}$	2	2	2	$\left(\frac{2}{5},0,4\right)$
II.8	$QL\phi_{\bar{\mathbf{5}},D}$	1	3	2	$\left(\frac{7}{30},\frac{3}{2},\frac{8}{3}\right)$

#	Model	d_1	d_2	d_3	C_r
II.9	$UE\phi_{\mathbf{5},\bar{D}}$	1	3	1	$\left(\frac{14}{15},0,\frac{8}{3}\right)$
II.10	$H_uD\phi_{\mathbf{24},X}$	3	2	1	$\left(\frac{19}{30},\frac{3}{2},\frac{8}{3}\right)$
II.11	$H_uL\phi_{\mathbf{1},S}$	1	1	2	$\left(\frac{3}{10},\frac{3}{2},0\right)$
II.12	$H_uL\phi_{\mathbf{24},S}$	1	1	2	$\left(\frac{3}{10},\frac{3}{2},0\right)$
II.13	$H_uL\phi_{\mathbf{24},W}$	$\frac{3}{2}$	$\frac{3}{2}$	1	$\left(\frac{3}{10},\frac{7}{2},0\right)$
II.14	$H_uH_d\phi_{\mathbf{1},S}$	1	1	2	$\left(\frac{3}{10},\frac{3}{2},0\right)$
II.15	$H_uH_d\phi_{\mathbf{24},S}$	1	1	2	$\left(\frac{3}{10},\frac{3}{2},0\right)$
II.16	$H_uH_d\phi_{\mathbf{24},W}$	$\frac{3}{2}$	$\frac{3}{2}$	1	$\left(\frac{3}{10},\frac{7}{2},0\right)$

$$W \sim \kappa X_1 X_2 \phi_{X_3}$$

only present with MSSM-Messenger mixing

$$\delta m^2_{X_1} = \left(d_1\left(\textstyle\sum_i d_i\kappa^2 - 2C_r g_r^2 - \frac{8\pi^2}{3}h\left(\frac{\Lambda}{M}\right)\frac{\Lambda^2}{M^2}\right) + 2d_1 d_3 y^2_{123} - d_1^{2p} d_2 y^2_{12p} + \frac{1}{2}d_1 d_2^{pq} y^2_{2pq}\right)\kappa^2\tilde{\Lambda}^2$$

$$\delta m^2_{X_2} = \delta m^2_{X_1}\{1 \leftrightarrow 2\}$$

$$\delta m^2_{X_a} = -\left(d_a^{1p} d_1 y^2_{1ap} + d_a^{2p} d_2 y^2_{2ap}\right)\kappa^2\tilde{\Lambda}^2$$

$$A_{X_{1,2}} = -d_{1,2}\kappa^2\tilde{\Lambda} \qquad A_t = y_t\left(A_{H_u} + A_{Q_3} + A_{U_3}\right)$$

Type II Models

EGMSB Formulas

#	Model	d_1	d_2	d_3	C_r
II.1	$QU\phi_{5,H_u}$	1	2	3	$\left(\frac{13}{30},\frac{3}{2},\frac{8}{3}\right)$
II.2	$UH_u\phi_{10,Q}$	2	3	1	$\left(\frac{13}{30},\frac{3}{2},\frac{8}{3}\right)$
II.3	$QH_u\phi_{10,U}$	1	3	2	$\left(\frac{13}{30},\frac{3}{2},\frac{8}{3}\right)$
II.4	$QD\phi_{\bar{5},H_d}$	1	2	3	$\left(\frac{7}{30},\frac{3}{2},\frac{8}{3}\right)$
II.5	$QH_d\phi_{\bar{5},D}$	1	3	2	$\left(\frac{7}{30},\frac{3}{2},\frac{8}{3}\right)$
II.6	$QQ\phi_{5,\bar{D}}$	2	2	4	$\left(\frac{1}{10},\frac{3}{2},4\right)$
II.7	$UD\phi_{\bar{5},D}$	2	2	2	$\left(\frac{2}{5},0,4\right)$
II.8	$QL\phi_{\bar{5},D}$	1	3	2	$\left(\frac{7}{30},\frac{3}{2},\frac{8}{3}\right)$

#	Model	d_1	d_2	d_3	C_r
II.9	$UE\phi_{5,\bar{D}}$	1	3	1	$\left(\frac{14}{15},0,\frac{8}{3}\right)$
II.10	$H_uD\phi_{24,X}$	3	2	1	$\left(\frac{19}{30},\frac{3}{2},\frac{8}{3}\right)$
II.11	$H_uL\phi_{1,S}$	1	1	2	$\left(\frac{3}{10},\frac{3}{2},0\right)$
II.12	$H_uL\phi_{24,S}$	1	1	2	$\left(\frac{3}{10},\frac{3}{2},0\right)$
II.13	$H_uL\phi_{24,W}$	$\frac{3}{2}$	$\frac{3}{2}$	1	$\left(\frac{3}{10},\frac{7}{2},0\right)$
II.14	$H_uH_d\phi_{1,S}$	1	1	2	$\left(\frac{3}{10},\frac{3}{2},0\right)$
II.15	$H_uH_d\phi_{24,S}$	1	1	2	$\left(\frac{3}{10},\frac{3}{2},0\right)$
II.16	$H_uH_d\phi_{24,W}$	$\frac{3}{2}$	$\frac{3}{2}$	1	$\left(\frac{3}{10},\frac{7}{2},0\right)$

$$W \sim \kappa X_1 X_2 \phi_{X_3}$$

only present with MSSM-Messenger mixing

$$\delta m^2_{X_1} = \left(d_1\left(\textstyle\sum_i d_i\kappa^2 - 2C_r g_r^2 - \frac{8\pi^2}{3}h\left(\frac{\Lambda}{M}\right)\frac{\Lambda^2}{M^2}\right) + 2d_1 d_3 y_{123}^2 - d_1^{2p} d_2 y_{12p}^2 + \frac{1}{2}d_1 d_2^{pq} y_{2pq}^2\right)\kappa^2\tilde{\Lambda}^2$$

$$\delta m^2_{X_2} = \delta m^2_{X_1}\{1 \leftrightarrow 2\}$$

$$\delta m^2_{X_a} = -\left(d_a^{1p} d_1 y_{1ap}^2 + d_a^{2p} d_2 y_{2ap}^2\right)\kappa^2\tilde{\Lambda}^2$$

$$A_{X_{1,2}} = -d_{1,2}\kappa^2\tilde{\Lambda} \qquad A_t = y_t\left(A_{H_u} + A_{Q_3} + A_{U_3}\right) \longleftarrow \text{double contribution to } A_t$$

Type II Models

EGMSB Formulas

#	Model	d_1	d_2	d_3	C_r
II.1	$QU\phi_{\mathbf{5},H_u}$	1	2	3	$\left(\frac{13}{30}, \frac{3}{2}, \frac{8}{3}\right)$
II.2	$UH_u\phi_{\mathbf{10},Q}$	2	3	1	$\left(\frac{13}{30}, \frac{3}{2}, \frac{8}{3}\right)$
II.3	$QH_u\phi_{\mathbf{10},U}$	1	3	2	$\left(\frac{13}{30}, \frac{3}{2}, \frac{8}{3}\right)$
II.4	$QD\phi_{\bar{\mathbf{5}},H_d}$	1	2	3	$\left(\frac{7}{30}, \frac{3}{2}, \frac{8}{3}\right)$
II.5	$QH_d\phi_{\bar{\mathbf{5}},D}$	1	3	2	$\left(\frac{7}{30}, \frac{3}{2}, \frac{8}{3}\right)$
II.6	$\cancel{QQ\phi_{\mathbf{5},\bar{D}}}$	2	2	4	$\left(\frac{1}{10}, \frac{3}{2}, 4\right)$
II.7	$UD\phi_{\bar{\mathbf{5}},D}$	2	2	2	$\left(\frac{2}{5}, 0, 4\right)$
II.8	$QL\phi_{\bar{\mathbf{5}},D}$	1	3	2	$\left(\frac{7}{30}, \frac{3}{2}, \frac{8}{3}\right)$

#	Model	d_1	d_2	d_3	C_r
II.9	$UE\phi_{\mathbf{5},\bar{D}}$	1	3	1	$\left(\frac{14}{15}, 0, \frac{8}{3}\right)$
II.10	$H_uD\phi_{\mathbf{24},X}$	3	2	1	$\left(\frac{19}{30}, \frac{3}{2}, \frac{8}{3}\right)$
II.11	$H_uL\phi_{\mathbf{1},S}$	1	1	2	$\left(\frac{3}{10}, \frac{3}{2}, 0\right)$
II.12	$H_uL\phi_{\mathbf{24},S}$	1	1	2	$\left(\frac{3}{10}, \frac{3}{2}, 0\right)$
II.13	$H_uL\phi_{\mathbf{24},W}$	$\frac{3}{2}$	$\frac{3}{2}$	1	$\left(\frac{3}{10}, \frac{7}{2}, 0\right)$
II.14	$H_uH_d\phi_{\mathbf{1},S}$	1	1	2	$\left(\frac{3}{10}, \frac{3}{2}, 0\right)$
II.15	$H_uH_d\phi_{\mathbf{24},S}$	1	1	2	$\left(\frac{3}{10}, \frac{3}{2}, 0\right)$
II.16	$H_uH_d\phi_{\mathbf{24},W}$	$\frac{3}{2}$	$\frac{3}{2}$	1	$\left(\frac{3}{10}, \frac{7}{2}, 0\right)$

Tachyons everywhere at high κ

Type II Models

EGMSB Formulas

#	Model	d_1	d_2	d_3	C_r
II.1	$QU\phi_{5,H_u}$	1	2	3	$\left(\frac{13}{30}, \frac{3}{2}, \frac{8}{3}\right)$
II.2	$UH_u\phi_{10,Q}$	2	3	1	$\left(\frac{13}{30}, \frac{3}{2}, \frac{8}{3}\right)$
II.3	$QH_u\phi_{10,U}$	1	3	2	$\left(\frac{13}{30}, \frac{3}{2}, \frac{8}{3}\right)$
II.4	$QD\phi_{\bar{5},H_d}$	1	2	3	$\left(\frac{7}{30}, \frac{3}{2}, \frac{8}{3}\right)$
II.5	$QH_d\phi_{\bar{5},D}$	1	3	2	$\left(\frac{7}{30}, \frac{3}{2}, \frac{8}{3}\right)$
II.6	$\cancel{QQ\phi_{5,\bar{D}}}$	2	2	4	$\left(\frac{1}{10}, \frac{3}{2}, 4\right)$
II.7	$UD\phi_{\bar{5},D}$	2	2	2	$\left(\frac{2}{5}, 0, 4\right)$
II.8	$QL\phi_{\bar{5},D}$	1	3	2	$\left(\frac{7}{30}, \frac{3}{2}, \frac{8}{3}\right)$

#	Model	d_1	d_2	d_3	C_r
II.9	$UE\phi_{5,\bar{D}}$	1	3	1	$\left(\frac{14}{15}, 0, \frac{8}{3}\right)$
II.10	$H_uD\phi_{24,X}$	3	2	1	$\left(\frac{19}{30}, \frac{3}{2}, \frac{8}{3}\right)$
II.11	$\cancel{H_uL\phi_{1,S}}$	1	1	2	$\left(\frac{3}{10}, \frac{3}{2}, 0\right)$
II.12	$\cancel{H_uL\phi_{24,S}}$	1	1	2	$\left(\frac{3}{10}, \frac{3}{2}, 0\right)$
II.13	$\cancel{H_uL\phi_{24,W}}$	$\frac{3}{2}$	$\frac{3}{2}$	1	$\left(\frac{3}{10}, \frac{7}{2}, 0\right)$
II.14	$H_uH_d\phi_{1,S}$	1	1	2	$\left(\frac{3}{10}, \frac{3}{2}, 0\right)$
II.15	$H_uH_d\phi_{24,S}$	1	1	2	$\left(\frac{3}{10}, \frac{3}{2}, 0\right)$
II.16	$H_uH_d\phi_{24,W}$	$\frac{3}{2}$	$\frac{3}{2}$	1	$\left(\frac{3}{10}, \frac{7}{2}, 0\right)$

Tachyons everywhere at high κ

m_ν too large

Type II Models

EGMSB Formulas

#	Model	d_1	d_2	d_3	C_r
II.1	$QU\phi_{\mathbf{5},H_u}$	1	2	3	$\left(\frac{13}{30}, \frac{3}{2}, \frac{8}{3}\right)$
II.2	$UH_u\phi_{\mathbf{10},Q}$	2	3	1	$\left(\frac{13}{30}, \frac{3}{2}, \frac{8}{3}\right)$
II.3	$QH_u\phi_{\mathbf{10},U}$	1	3	2	$\left(\frac{13}{30}, \frac{3}{2}, \frac{8}{3}\right)$
II.4	$QD\phi_{\bar{\mathbf{5}},H_d}$	1	2	3	$\left(\frac{7}{30}, \frac{3}{2}, \frac{8}{3}\right)$
II.5	$QH_d\phi_{\bar{\mathbf{5}},D}$	1	3	2	$\left(\frac{7}{30}, \frac{3}{2}, \frac{8}{3}\right)$
II.6	$\cancel{QQ\phi_{\mathbf{5},\bar{D}}}$	2	2	4	$\left(\frac{1}{10}, \frac{3}{2}, 4\right)$
II.7	$UD\phi_{\bar{\mathbf{5}},D}$	2	2	2	$\left(\frac{2}{5}, 0, 4\right)$
II.8	$QL\phi_{\bar{\mathbf{5}},D}$	1	3	2	$\left(\frac{7}{30}, \frac{3}{2}, \frac{8}{3}\right)$

#	Model	d_1	d_2	d_3	C_r
II.9	$UE\phi_{\mathbf{5},\bar{D}}$	1	3	1	$\left(\frac{14}{15}, 0, \frac{8}{3}\right)$
II.10	$H_uD\phi_{\mathbf{24},X}$	3	2	1	$\left(\frac{19}{30}, \frac{3}{2}, \frac{8}{3}\right)$
II.11	$\cancel{H_uL\phi_{\mathbf{1},S}}$	1	1	2	$\left(\frac{3}{10}, \frac{3}{2}, 0\right)$
II.12	$\cancel{H_uL\phi_{\mathbf{24},S}}$	1	1	2	$\left(\frac{3}{10}, \frac{3}{2}, 0\right)$
II.13	$\cancel{H_uL\phi_{\mathbf{24},W}}$	$\frac{3}{2}$	$\frac{3}{2}$	1	$\left(\frac{3}{10}, \frac{7}{2}, 0\right)$
II.14	$\cancel{H_uH_d\phi_{\mathbf{1},S}}$	1	1	2	$\left(\frac{3}{10}, \frac{3}{2}, 0\right)$
II.15	$\cancel{H_uH_d\phi_{\mathbf{24},S}}$	1	1	2	$\left(\frac{3}{10}, \frac{3}{2}, 0\right)$
II.16	$\cancel{H_uH_d\phi_{\mathbf{24},W}}$	$\frac{3}{2}$	$\frac{3}{2}$	1	$\left(\frac{3}{10}, \frac{7}{2}, 0\right)$

Tachyons everywhere at high κ

m_ν too large

Exacerbate $\mu - B_\mu$ problem

#	Model	d_1	d_2	d_3	C_r
II.1	$QU\phi_{5,H_u}$	1	2	3	$\left(\frac{13}{30},\frac{3}{2},\frac{8}{3}\right)$
II.2	$UH_u\phi_{10,Q}$	2	3	1	$\left(\frac{13}{30},\frac{3}{2},\frac{8}{3}\right)$
II.3	$QH_u\phi_{10,U}$	1	3	2	$\left(\frac{13}{30},\frac{3}{2},\frac{8}{3}\right)$
II.4	$\cancel{QD\phi_{\bar{5},H_d}}$	1	2	3	$\left(\frac{7}{30},\frac{3}{2},\frac{8}{3}\right)$
II.5	$\cancel{QH_d\phi_{\bar{5},D}}$	1	3	2	$\left(\frac{7}{30},\frac{3}{2},\frac{8}{3}\right)$
II.6	$\cancel{QQ\phi_{\bar{5},D}}$	2	2	4	$\left(\frac{1}{10},\frac{3}{2},4\right)$
II.7	$UD\phi_{\bar{5},D}$	2	2	2	$\left(\frac{2}{5},0,4\right)$
II.8	$\cancel{QL\phi_{\bar{5},D}}$	1	3	2	$\left(\frac{7}{30},\frac{3}{2},\frac{8}{3}\right)$

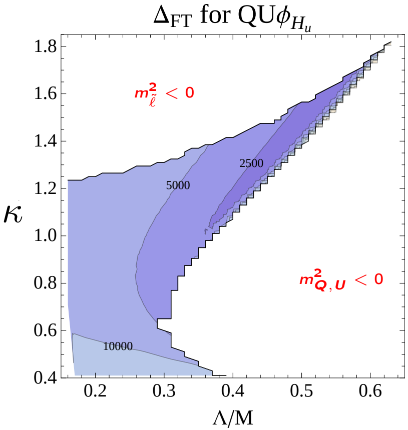
#	Model	d_1	d_2	d_3	C_r
II.9	$\cancel{UE\phi_{5,\bar{D}}}$	1	3	1	$\left(\frac{14}{15},0,\frac{8}{3}\right)$
II.10	$\cancel{H_uD\phi_{24,X}}$	3	2	1	$\left(\frac{19}{30},\frac{3}{2},\frac{8}{3}\right)$
II.11	$\cancel{H_uL\phi_{1,S}}$	1	1	2	$\left(\frac{3}{10},\frac{3}{2},0\right)$
II.12	$\cancel{H_uL\phi_{24,S}}$	1	1	2	$\left(\frac{3}{10},\frac{3}{2},0\right)$
II.13	$\cancel{H_uL\phi_{24,W}}$	$\frac{3}{2}$	$\frac{3}{2}$	1	$\left(\frac{3}{10},\frac{7}{2},0\right)$
II.14	$\cancel{H_uH_d\phi_{1,S}}$	1	1	2	$\left(\frac{3}{10},\frac{3}{2},0\right)$
II.15	$\cancel{H_uH_d\phi_{24,S}}$	1	1	2	$\left(\frac{3}{10},\frac{3}{2},0\right)$
II.16	$\cancel{H_uH_d\phi_{24,W}}$	$\frac{3}{2}$	$\frac{3}{2}$	1	$\left(\frac{3}{10},\frac{7}{2},0\right)$

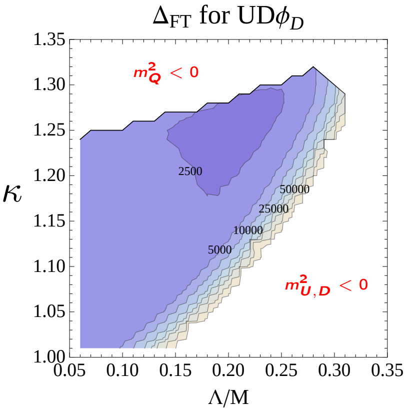
Tachyons everywhere at high κ

m_ν too large

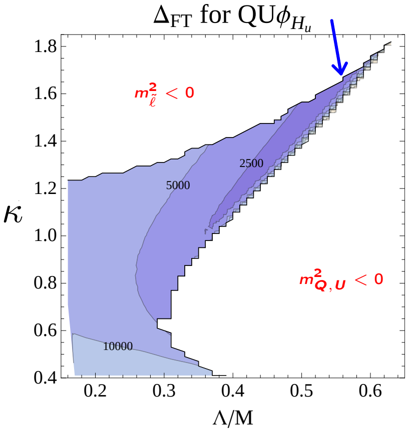
Exacerbate $\mu - B_\mu$ problem

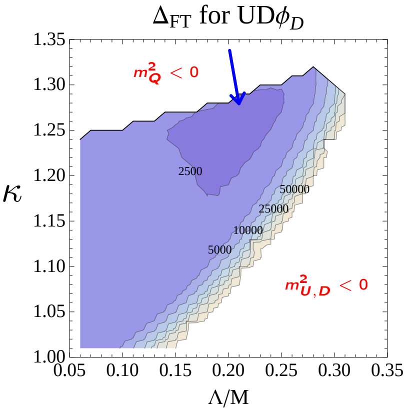
Tuning bad


Δ_{FT} for $QU\phi_{H_u}$
$m^2_{\tilde{\ell}} < 0$
$m^2_{Q,U} < 0$
2500
5000
10000
κ
Λ/M


Δ_{FT} for $UD\phi_D$
$m^2_Q < 0$
$m^2_{U,D} < 0$
2500
50000
25000
10000
5000
κ
Λ/M

Type II Models
Tuning



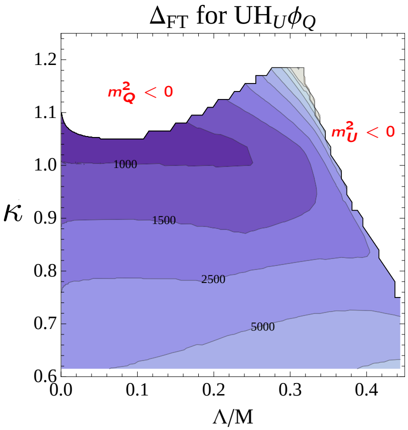


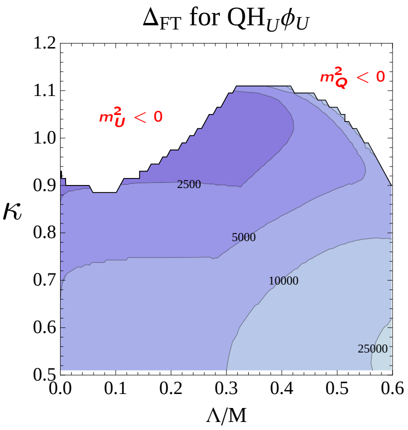
$\Delta_{FT} \sim 1800$ (3.5× best MSSM)

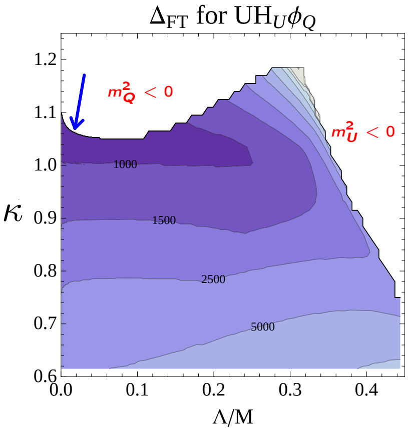
$\Delta_{FT} \sim 2150$ (4× best MSSM)

Type II Models

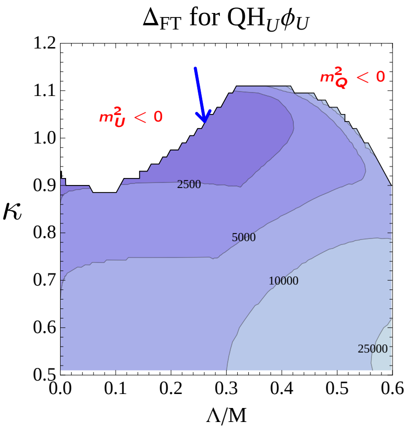
Tuning







$\Delta_{FT} \sim 850$ (1.5× best MSSM!)



$\Delta_{FT} \sim 1500$ (3× best MSSM)

Type II Models

Tuning

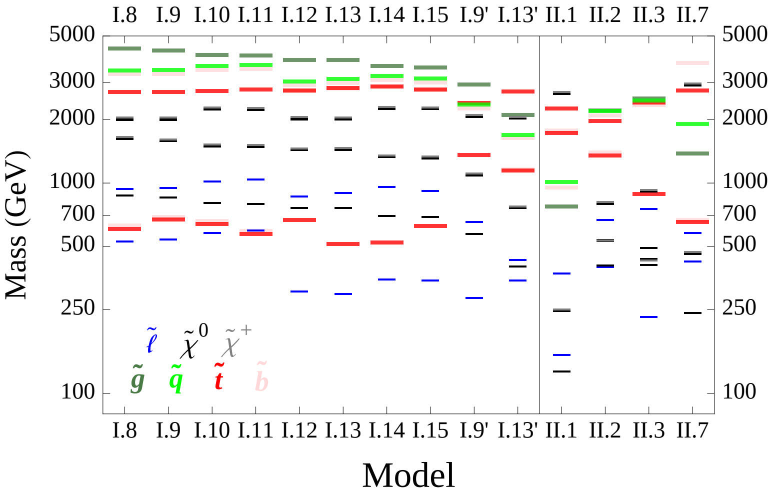
#	Coupling	$\lvert\Delta b\rvert$	Best Point $\{\frac{\Lambda}{M}, \lambda\}$	$\lvert A_t\rvert / M_S$	$M_{\tilde{g}}$	M_S	$\lvert\mu\rvert$	Tuning
II.1	$QU\phi_{5,H_u}$	1	$\{0.55, 1.64\}$	2.02	769	1965	2738	1800
II.2	$UH_u\phi_{10,Q}$	3	$\{0.009, 1.067\}$	2.14	2203	1628	543	850
II.3	$QH_u\phi_{10,U}$	3	$\{0.269, 1.05\}$	2.27	2514	1458	439	1500
II.4	$QD\phi_{\bar{5},H_d}$	1	$\{0.37, 1.2\}$	1.78	2597	1829	3553	3020
II.5	$QH_d\phi_{\bar{5},D}$	1	$\{0.15, 1.19\}$	1.45	2497	2108	3773	6050
II.6	$QQ\phi_{5,\bar{D}}$	1	$\{0.45, 0.1\}$	0.22	7943	9870	3610	5000
II.7	$UD\phi_{\bar{5},D}$	1	$\{0.21, 1.26\}$	2.34	1374	1334	2998	2150
II.8	$QL\phi_{\bar{5},D}$	1	$\{0.14, 1.2\}$	1.51	1501	1204	2203	3700
II.9	$UE\phi_{5,\bar{D}}$	1	$\{0.445, 1.46\}$	1.89	2004	1750	3373	2730
II.10	$H_uD\phi_{24,X}$	5	$\{0.42, 1.45\}$	2.13	2943	1649	282	3500
II.11	$H_uL\phi_{1,S}$	1^*	$\{0.15, 0.675\}$	0.54	7103	8166	3714	4930
II.12	$H_uL\phi_{24,S}$	5	$\{0.296, 0.96\}$	0.53	12629	9660	3333	3780
II.13	$H_uL\phi_{24,W}$	5	$\{0.212, 0.96\}$	0.65	11487	8710	3687	3380
II.14	$H_uH_d\phi_{1,S}$	1^*	$\{0.125, 0.675\}$	0.55	7049	8051	3255	5000
II.15	$H_uH_d\phi_{24,S}$	5	$\{0.20, 1.00\}$	0.57	12047	9213	1628	4220
II.16	$H_uH_d\phi_{24,W}$	5	$\{0.2, 0.946\}$	0.64	11571	8789	3665	3460

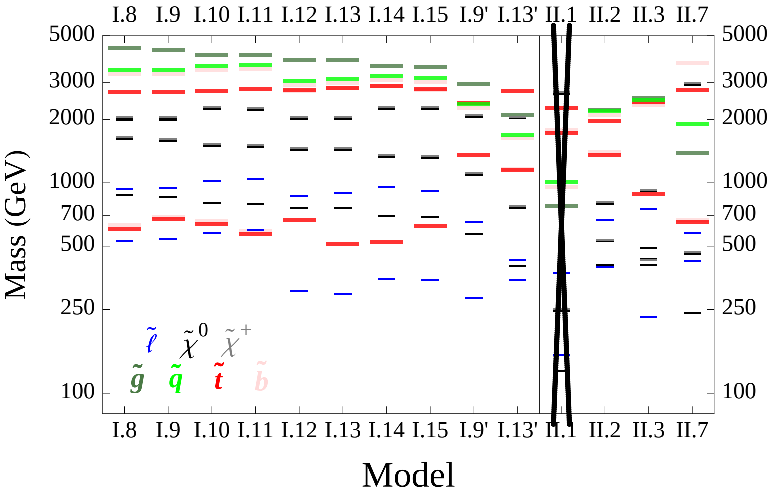
Types of models
Tuning & Flavor

	Type I			Type II	
	Higgs	Q-class	U-class	w/ mixing	w/o mixing
	$\lambda H_u \Phi\tilde{\Phi}$	$\lambda Q\Phi\tilde{\Phi}$	$\lambda U\Phi\tilde{\Phi}$	$\lambda H_u Q \Phi_U$	$\lambda U E \Phi_{\bar{D}}$
Tuning:	BAD	GOOD	GOOD	GOOD	BAD
Flavor:	MFV	???	???	???	???

Types of models
Tuning & Flavor

	Type I			Type II	
	Higgs	Q-class	U-class	w/ mixing	w/o mixing
	$\lambda H_u \Phi \tilde{\Phi}$	$\lambda Q \Phi \tilde{\Phi}$	$\lambda U \Phi \tilde{\Phi}$	$\lambda H_u Q \Phi_U$	$\lambda U E \Phi_{\bar{D}}$
Tuning:	BAD	GOOD	GOOD	GOOD	BAD
Flavor:	MFV	???	???	???	DON'T CARE!

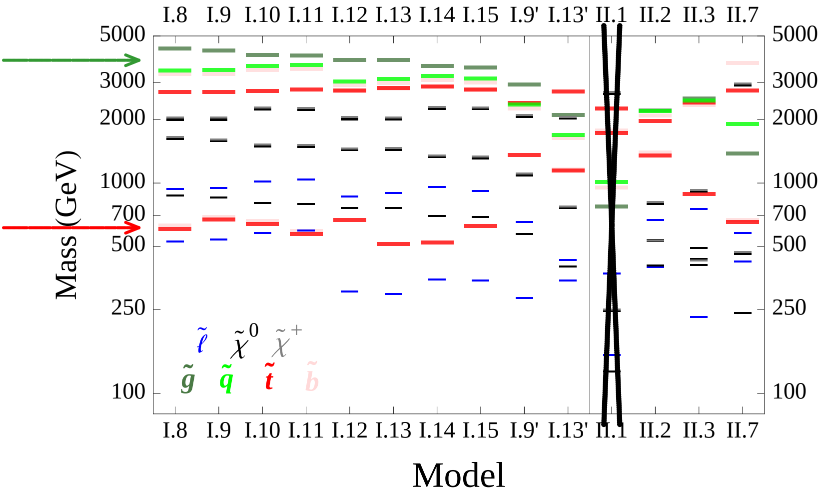

I.8 I.9 I.10 I.11 I.12 I.13 I.14 I.15 I.9' I.13' II.1 II.2 II.3 II.7
5000
3000
2000
1000
700
500
250
100
Mass (GeV)
Model
$\tilde{\ell}$ $\tilde{\chi}^0$ $\tilde{\chi}^+$
$\tilde{g}$ $\tilde{q}$ $\tilde{t}$ $\tilde{b}$



I.8 I.9 I.10 I.11 I.12 I.13 I.14 I.15 I.9' I.13' II.1 II.2 II.3 II.7
5000
3000
2000
1000
700
500
250
100
Mass (GeV)
Model

LHC Phenomenology

Spectra



In general, heavy spectra!

Are $m_h = 125$ GeV and no SUSY at 8 TeV really correlated problems?

In general, heavy spectra!

Are $m_h = 125$ GeV and no SUSY at 8 TeV really correlated problems?

1. $\tilde{t}$ NLSP or co-NLSP (bounds reach 750 GeV now)
2. $\tilde{t}$: $\tilde{B}$: $\tilde{\ell}$ — Decays of $\tilde{t} \to t\tilde{\chi}^0 \to t\ell^\pm\tilde{\ell}^\mp \to t\ell^\pm\tilde{\tau}^\mp \Rightarrow$ multieptons
3. $\tilde{t}$: $\tilde{\ell}$ — $\tilde{t} \to b\nu\tilde{\tau}^+ \to b\nu\tau^+\tilde{G} \;\Rightarrow\; bb\tau^+\tau^- + \not{E}_T$

Last case especially exciting!

In general, heavy spectra!

Are $m_h = 125$ GeV and no SUSY at 8 TeV really correlated problems?

1. $\tilde{t}$ NLSP or co-NLSP (bounds reach 750 GeV now)
2. $\tilde{t} : \tilde{B} : \tilde{\ell}$ — Decays of $\tilde{t} \to t\tilde{\chi}^0 \to t\ell^\pm\tilde{\ell}^\mp \to t\ell^\pm\tilde{\tau}^\mp \Rightarrow$ multieptons
3. $\tilde{t} : \tilde{\ell}$ — $\tilde{t} \to b\nu\tilde{\tau}^+ \to b\nu\tau^+\tilde{G} \;\Rightarrow\; bb\tau^+\tau^- + \not{E}_T$

Last case especially exciting!

Now on to flavor!

In the SM, flavor is only violated by the CKM – W charged current

To constrain NP, flavor observables that vanish at tree level in SM are best

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Observable	Experiment	SM prediction
Δm_K	$(3.484 \pm 0.006) \times 10^{-15}$ GeV	$-^*$
Δm_{B_d}	$(3.36 \pm 0.02) \times 10^{-13}$ GeV	$(3.56 \pm 0.60) \times 10^{-13}$ GeV
Δm_{B_s}	$(1.169 \pm 0.0014) \times 10^{-11}$ GeV	$(1.13 \pm 0.17) \times 10^{-11}$ GeV
Δm_D	$(6.2^{+2.7}_{-2.8}) \times 10^{-15}$ GeV	$-$
$Br(K^+ \to \pi^+ \nu\bar{\nu})$	$(1.7 \pm 1.1) \times 10^{-10}$	$(7.8 \pm 0.8) \times 10^{-11}$
$Br(B \to X_s \gamma)$	$(3.40 \pm 0.21) \times 10^{-4}$	$(3.15 \pm 0.23) \times 10^{-4}$
$Br(B \to X_d \gamma)$	$(1.41 \pm 0.57) \times 10^{-5}$	$(1.54^{+0.26}_{-0.31}) \times 10^{-5}$
$Br(B_s \to \mu^+\mu^-)$	$(2.9 \pm 0.7) \times 10^{-9}$	$(3.65 \pm 0.23) \times 10^{-9}$
$Br(B_d \to \mu^+\mu^-)$	$(3.6^{+1.6}_{-1.4}) \times 10^{-10}$	$(1.06 \pm 0.09) \times 10^{-10}$

Flavor violation can be parameterized by dimension 5 & 6 operators

- Dimension 5: $\frac{1}{\Lambda}\bar{q}_1\sigma^{\mu\nu}q_2 F_{\mu\nu}$, $\frac{1}{\Lambda}\bar{q}_1\sigma^{\mu\nu}q_2 G_{\mu\nu}$
  - Radiative $\Delta F = 1$: $b \to s\gamma$, $b \to d\gamma$

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  - Meson Mixing $\Delta F = 2$: Δm_K, Δm_D, Δm_{B_s}, Δm_{B_d}
- Leptonic Dimension 6: $\frac{1}{\Lambda^2}\left(\bar{q}_1q_2\right)\left(\mu^+\mu^-\right)$, $\frac{1}{\Lambda^2}\left(\bar{q}_1\gamma_\mu q_2\right)\left(\bar{\nu}\gamma^\mu\nu\right)$, etc.
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Bounds on some operators *much* stronger than others, even for the same observable:

$$\begin{array}{ll} \text{OpA — } \Delta m_K : \left(\bar{s}_L\gamma^\mu d_L\right)^2 & \Rightarrow \Lambda > 9.8\times 10^2 \text{ TeV} \\ \text{OpB — } \Delta m_K : \left(\bar{s}_R d_L\right)\left(\bar{s}_L d_R\right) & \Rightarrow \Lambda > 1.8\times 10^4 \text{ TeV} \end{array}$$

(Isidori, Nir, Perez 2010)

$$M_d^2 = \left(\begin{array}{ccc|ccc} m^2_{Q,11} & m^2_{Q,12} & m^2_{Q,13} & A^\dagger_{d,11} v_d & A^\dagger_{d,12} v_d & A^\dagger_{d,13} v_d \\ m^2_{Q,21} & m^2_{Q,22} & m^2_{Q,23} & A^\dagger_{d,21} v_d & A^\dagger_{d,22} v_d & A^\dagger_{d,23} v_d \\ m^2_{Q,31} & m^2_{Q,32} & m^2_{Q,33} & A^\dagger_{d,31} v_d & A^\dagger_{d,32} v_d & A^\dagger_{d,33} v_d \\ \hline A_{d,11} v_d & A_{d,12} v_d & A_{d,13} v_d & m^2_{D,11} & m^2_{D,12} & m^2_{D,13} \\ A_{d,21} v_d & A_{d,22} v_d & A_{d,23} v_d & m^2_{D,11} & m^2_{D,12} & m^2_{D,13} \\ A_{d,31} v_d & A_{d,32} v_d & A_{d,33} v_d & m^2_{D,11} & m^2_{D,12} & m^2_{D,13} \end{array}\right)$$

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$$M_d^2 = \tilde{m}^2_{d,0}(\mathbf{1} + \delta^{XY}), \qquad \text{where } \tilde{m}^2_{d,0} = \frac{1}{6}\,\mathrm{Tr}(M_d^2)$$

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LL RL
LR RR

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Toward a Flavor Story

The Task at Hand

$$W = \kappa_3 Q_3 \Phi\tilde{\Phi} \to W = \kappa_i Q_i \Phi\tilde{\Phi}$$

We want to compute bounds on couplings κ_i from flavor observables

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To do this we need the following:

- Compute general non-MFV soft masses at the messenger scale
- Run them down to the SUSY scale, including full 3x3 CKM & CPV
- Compute 1-loop Wilson coefficients for all operators of interest
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We could not find a suitable public code to do all of this, so we wrote it!

FormFlavor

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(Now, FlavorKit exists which does similar things with SARAH and Spheno)

In the third-generation dominant limit ($y_i = 0$ for $i \neq t, b$)

Q-class: $$\delta m^2 \sim \left(\begin{array}{ccc|ccc} \kappa_1^*\kappa_1\tilde{\Lambda}^2 & \kappa_1^*\kappa_2\tilde{\Lambda}^2 & \kappa_1^*\kappa_3\tilde{\Lambda}^2 & 0 & 0 & \kappa_1^*\kappa_3\, yv\tilde{\Lambda} \\ \kappa_2^*\kappa_1\tilde{\Lambda}^2 & \kappa_2^*\kappa_2\tilde{\Lambda}^2 & \kappa_2^*\kappa_3\tilde{\Lambda}^2 & 0 & 0 & \kappa_2^*\kappa_3\, yv\tilde{\Lambda} \\ \kappa_3^*\kappa_1\tilde{\Lambda}^2 & \kappa_3^*\kappa_2\tilde{\Lambda}^2 & \kappa_3^*\kappa_3\tilde{\Lambda}^2 & 0 & 0 & \kappa_3^*\kappa_3\, yv\tilde{\Lambda} \\ \hline 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ \kappa_3^*\kappa_1\, yv\tilde{\Lambda} & \kappa_3^*\kappa_2\, yv\tilde{\Lambda} & \kappa_3^*\kappa_3\, yv\tilde{\Lambda} & 0 & 0 & \kappa_3^*\kappa_3\, y^2\tilde{\Lambda}^2 \end{array}\right)$$

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Features:

- Q-class matrix form for M_d^2 and M_u^2, U-class only for M_u^2
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Toward a Flavor Story

Our EGMSB Mass Matrix: Chiral Flavor Violation

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General χFV arises simply from symmetries, e.g anarchic Q, vanilla $U, D \Rightarrow Q\chi$FV

At best tuned point, for $(\kappa_1, \kappa_2) = (0, 0)$, $\delta m^2_{Q,33} < 0$

$$\delta m^2_{Q,ab} = d_Q \left((d_\phi + d_Q)\kappa^2 - 2C_r g_r^2 - \frac{16\pi^2}{3} h\left(\frac{\Lambda}{M}\right)\frac{\Lambda^2}{M^2} \right) \kappa_a^* \kappa_b \tilde{\Lambda}^2$$

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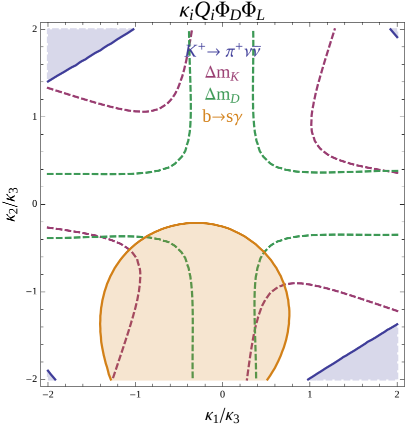
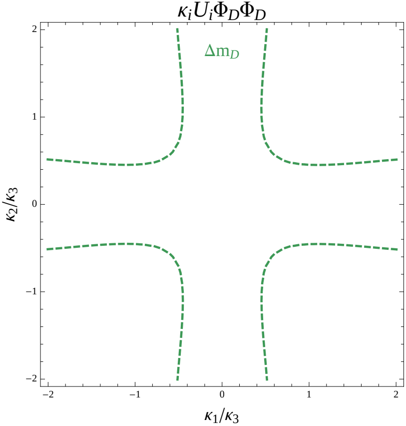
Instead, we fix Λ, but vary M to fix the lightest eigenvalue in the m^2_Q block

Note: Eigenvalues$[c\tilde{\Lambda}^2 \mathbf{1}_3 - F\left(\kappa, \frac{\Lambda}{M}\right) \tilde{\Lambda}^2 \kappa_i^* \kappa_j] = \{c, c, c - F\left(\kappa, \frac{\Lambda}{M}\right) \kappa^2\} \tilde{\Lambda}^2$

Type I Q-class and U-class Constraints
2σ Constraints





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What happened to the SUSY flavor problem?

Why so few constraints even for $\mathcal{O}(1)$ couplings?

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Weak for several reasons:

1. U-class only in up sector – safer than down
2. $m_h = 125$ GeV $\Rightarrow$ most squarks at ~ 3 TeV
3. Effective operator bounds can exaggerate the problem
4. Flavor violation is from rank 1 tensor, suppresses FV a bit
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From SUSY MIA:

$$\frac{1}{\Lambda^2}\left(\bar{s}_L\gamma^\mu d_L\right)^2 = \frac{\alpha_s^2}{216\tilde{m}^2}\left(\delta_{12}^{LL}\right)^2\left(\bar{s}_L\gamma^\mu d_L\right)^2 : \; \Lambda > 10^3\,\text{TeV} \Rightarrow \tilde{m} > 5\,\text{TeV}$$

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5. Chiral Flavor Violation (χFV) Flavor Texture

We fix lightest e.value: $M^2_{Q,ij} \sim M^2\mathbf{1} - X\kappa_i\kappa_j \Rightarrow \{M^2, M^2, M^2 - X\kappa^2\}$

$X\kappa^2 \sim M^2 \Rightarrow \delta^{LL}_{ij} \sim \frac{3\kappa_i\kappa_j}{2(\kappa_1^2+\kappa_2^2+\kappa_3^2)}$ for $\kappa_1 = \kappa_2 = \kappa_3$, $\delta^{LL}_{ij} \sim \frac{1}{2}$

Type I Q-class and U-class Constraints

What happened to the SUSY flavor problem?

Why so few constraints even for $\mathcal{O}(1)$ couplings?

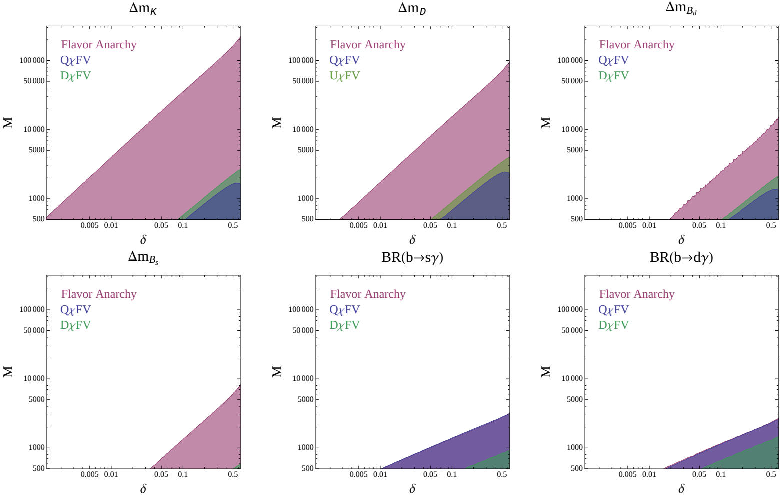
Weak for several reasons:

1. U-class only in up sector – safer than down
2. $m_h = 125$ GeV $\Rightarrow$ most squarks at ~ 3 TeV
3. Effective operator bounds can exaggerate the problem
4. Flavor violation is from rank 1 tensor, suppresses FV a bit
5. Chiral Flavor Violation (χFV) Flavor Texture

Type I Q-class and U-class Constraints

χFV Texture

Q-class EGMSB mass matrix has FV in LL and select LR/RL elements



Why is Δm_K so weak??? (Compared to Flavor Anarchy)

Several factors work in the same direction: $\frac{\Delta m_K(\text{Anarchy})}{\Delta m_K(\chi\text{FV})} \sim$

χFV: Contributes to O_V^{LL} ONLY

$$O_V^{LL} = (\bar{s}\gamma^\mu P_L d)^2$$

Anarchy: All wilson operators

$$O_S^{LR} = (\bar{s}P_L d)(\bar{s}P_R d)$$

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- HME: $\frac{8}{24} B_V^{LL} \sim 0.19$

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Work together to make Δm_X constraints weak!

Future Constraints / Discovery

Prospects

On the $3-5$ year time scale, several things should happen:

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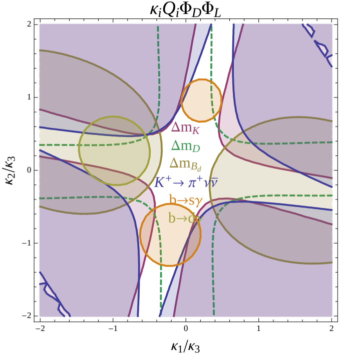

Observable	Improvement	Projected
Δm_K	Theory	10%
Δm_{B_d}	Theory	$\sim$10%
Δm_{B_s}	Theory	5%
Δm_D	None	–
$Br(K^+ \to \pi^+ \nu \bar{\nu})$	Experiment	10%
$Br(B \to X_s \gamma)$	Experiment	7%
$Br(B \to X_d \gamma)$	Experiment	24%
$Br(B_s \to \mu^+ \mu^-)$	Experiment	15%
$Br(B_d \to \mu^+ \mu^-)$	Experiment	$\sim$35%

Flavor in Type II models

Especially UH_u and QH_u

Turning on small κ_1, κ_2 makes these models encounter tachyons:

In $UH_u\Phi_Q$

$$\delta m^2_{Q,33} = -y_t^2(2\kappa_3^*\kappa_3 + 3\kappa^2)\tilde{\Lambda}^2$$

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(Note: still χFV, so flavor is fine in narrow window of validity)

Types of models

Tuning & Flavor

	Type I			Type II	
	Higgs	Q-class	U-class	w/ mixing	w/o mixing
	$\lambda H_u \Phi \tilde{\Phi}$	$\lambda Q \Phi \tilde{\Phi}$	$\lambda U \Phi \tilde{\Phi}$	$\lambda H_u Q \Phi_U$	$\lambda U E \Phi_{\bar{D}}$
Tuning:	BAD	GOOD	GOOD	GOOD	BAD
Flavor:	MFV	OKAY	GOOD	TACHYONS	DON'T CARE!

Summary & Future Directions

- We examined tuning in EGMSB models that get $m_h = 125$ GeV
- Wrote FormFlavor to investigate flavor in this non-MFV model
- Flavor constraints are weak in these models
  - Mostly due to the special χFV texture
  - Δm_D and $b \to s\gamma$ dominate
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Future directions

- We only focused on flavor observables, we want to look at CP as well
- The χFV texture deserves further study on its own (like MFV)
- We plan to make FormFlavor public
- Collider phenomenology is very interesting, especially in the FV case
  – Complete model for Flavored Naturalness (Blanke, Giudice, Paradisi, Perez, Zupan)